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An experiment on a sand-dune environment in Southern Venetian coast based on GPR, VES and documentary evidence

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Abstract

The internal structures of some surviving sand dunes and the ancient shore-lines along the coast south of Venice have been investigated integrating Ground Probing Radar (GPR) profiles, Vertical Electrical Soundings (VES) and water conductivity measurements in some boreholes. The GPR penetration depth has been limited (4-5 m, using a 400 MHz antenna) by the high conductivity of salt water saturating pores of the shallow sediments. On the other hand, the excellent spatial resolution of the radar survey provided an estimate of internal dune bedding features, such as cross lamination and forwarding ancient covered coast-lines dated in the Thirties. The interpretation of the data, in particular along one line 360 m long intercepting a sizable sand-dune bank, seems to offer clues to the evolutional history of the coast line and the depth of transition from fresh-water to brackish-salt water. The water table was detected with electrical measurements and direct observations in boreholes, whereas the transition between fresh and salt water (brackish water) was pointed out indirectly by the high energy absorption and total back-reflection of the EM waves, encountered at this boundary, and directly by the strong decrease in VES resistivity values.

Key words *GPR-coastal dunes – groundwater – salt-water intrusion – littoral evolution*

1. Research topics

Our basic hypothesis was that groundwater can be detected if the water saturation of rocks causes a strong increase in relative dielectric constant. When a rock is saturated by water, for instance, the resulting EM impedance contrast between the unsaturated and saturated zones breeds the reflection of the GPR pulse. In this way, in many cases the groundwater table can be detected with a careful selection of the GPR antenna central frequency for optimum penetration depth and spatial resolution. Then, a radar stratigraphic analysis can recognize the facies responsible for reflections, the correlation of radar patterns with specific sedimentary environments and hydrological characterization of the subsurface (Van Overmeeren, 1998).

The area chosen for the test is the coast surrounding Sottomarina (Venice-Italy), in the southern basin of the Venice Lagoon (fig. 1). Sandy composition of dunes and ancient covered shoreline offer good conditions for GPR surveying. The dunes, 5-10 m high and some kilometers long, are naturally preserved in front of the sea and often altered by the farmers activity in the back side sector. Because of the high porosity and permeability of the sands, these sedimentary structures can be an excellent res-

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Fig. 1. Location of the working area in a satellite image of the Venetian Lagoon.

ervoir of meteoric water and could be exploited as a source of irrigation waters. They constitute a very important aquifer being the only shallow fresh water bulk above the salt water edge along the coastal strip.

In the Sottomarina coast, the groundwater is used for irrigation of many small horticultural plants. This area should require detailed mapping of the shallow subsurface to point out the groundwater reserves and the delicate balance between groundwater exploitation and ecological implications. On the sand dunes, monitoring the daily or seasonal variations of the groundwater level could lead to a better understanding of the relations between local and regional aquifers. The depositional and transporting processes of saltation, grainfall and grainflow produce internal bedding structures appearing as various sorts of laminations (Hunter, 1977); furthermore, grain size distributions vary among different types of bedding structures. It is also evident that the internal stratigraphical patterns within a dune are governed by the wind speed and direction (Rubin and Hunter, 1983).

Our trial of singling out a methodology extensible to investigations on wider areas was based, besides GPR, also on other techniques: Vertical Electrical Soundings (VES), water conductivity sampling analysis in boreholes and evidence of the historical shore-line variations, essentially based on a series of historical maps and aerial photographs. Other conventional geophysical exploration techniques were considered too slow and intensive field-working for our limited experiment; moreover the spatial resolution may not be sufficient for imaging dune internal beddings (McKee, 1966).

The GPR survey was carried out in the singlefold acquisition (or monostatic) mode, with the antenna manually towed at constant speed along profiles perpendicular to the shore line and to the strike of the dune bodies. The main parameter acting on electromagnetic wave penetration is the electrical conductivity and the permittivity of the media (Ulriksen, 1982; Parkhomenko, 1967). In the coastal environment, where sea water intrusions occur, the depth of penetration of GPR is severely limited by the strong increase in conductivity caused by the presence of saline water. The presence of clays and limes in the subsurface sediments can also reduce the penetration depth of GPR due to the attenuation caused by polarisation effects of EM energy in the presence of colloidal clay particles. Such EM energy attenuation is also frequency depending, since low frequencies are attenuated less than high frequencies. Since the GPR skill to resolve fine subsurface features decreases at lower frequencies, the selection of the optimal central frequency of the antenna for a specific application implies a compromise between the required resolution and the achievable depth of penetration. Some tests performed with 100 MHz and 400 MHz antennas have shown that the latter is more effective for our purposes, being very resolutive, and on the other side the penetration depth is in both cases limited by the shallow presence of salt water.

2. Survey and data interpretation

Three GPR profiles, orthogonal to the coastline were performed with a 400 MHz antenna; the longest (360 m) and the most representative of them provided the radargram shown in fig. 2.

The GPR data recorded in the field were processed with a two-dimensional filtering and a conventional image processing technique (vertical IIR low-pass filter with F = 640 MHz; vertical IIR high pass filter with F = 40 MHz; horizontal IIR stack with TC = 3; horizontal normalization with scan/marks = 56; horizontal stack 2; surface normalization level: (4) was applied to the data. Since the GPR data were collected directly as zero-offset (monostatic mode) radargram it was not possible to perform velocity analysis. Instead, we profited by known depths of reflectors such as the dune base and buried objects (shrubs), for computing the EM velocity values for the site. The linear depth scale in the radargram shown in fig. 2 was assumed on the basis of a single average velocity of 10 cm/ns and valid for the standard GPR penetration depth. Also, a static trace-shifting procedure was implemented for elevation correction to partially remove the effect of dune topography. This procedure is accurate for moving to the correct position the nearly horizontal reflectors, such as the shore-plains and the dunes bases. The process is not fully satisfactory to give the exact position of the steep reflectors such as eolian cross-strata, which cannot be migrated to their correct spatial position by trace-shifting.

Therefore, the value of the angle of inclination of the cross-strata cannot be calculated from the radargram included in this paper. Furthermore, antenna inclination corrections should be taken into account for removing distortions introduced in the radargrams by likely extreme variations occurring if the antenna is towed along steep surfaces such as the downwind face of a dune.

Figure 2 shows a processed radargram depicting the structure of the subsurface along the profile crossing the shore and the dune apparatus from the coast-line eastwards to the back-dune westwards. The two way travel time range

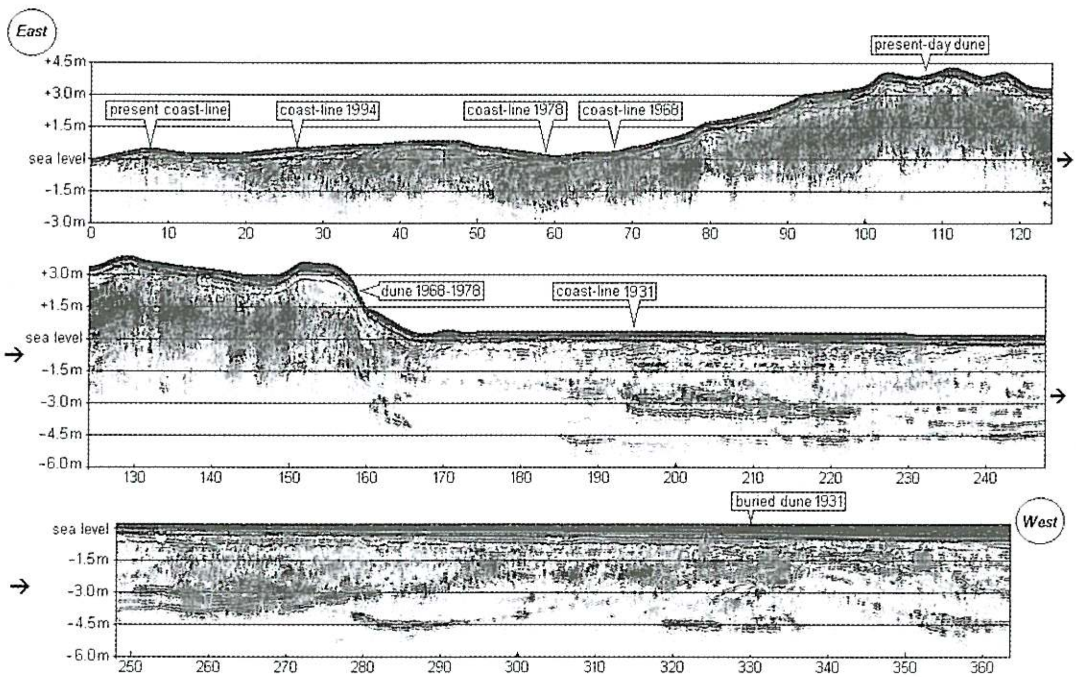

Fig. 2. Radargram recorded along a profile 360 m long, perpendicular to Sottomarina coast, starting from the sea-shore (eastwards), going through a dune and the back-dune plain (westwards). Settings: Scans/s: 32; Samples/scan: 512; Bits/sample: 8; Time range: 100 ns; Range Gains (dB): 18, 62, 62, 62, 67.

is 100 ns, corresponding, in our estimate, to a depth range of approximately 5 m, under the most favourable conditions. It is noted that the GPR did not detect any bounding surfaces inside the dune body, although it is known that dunes usually contain several internal bounding surfaces (Hunter, 1977). Thus, GPR does not seem to be effective for detecting interfaces solely marked by variations in grain packing density, such as those occurring at internal bounding surfaces (Schenk *et al.*, 1993). The strong GPR reflections observed at laminations boundaries in the eastern and central parts (shore and dune body) of the radargram shown in fig. 2 could be due to significant impedance contrasts provided by heavy minerals, such as magnetite and other iron-oxides, present in the abundant silicates (biotite), with lamellar habitus, deposited in sharp levels under the wind action. The inclined reflectors in the underground near the shore at the eastern side of the profile were interpreted as traces of ancient buried coast lines, progressing from the Thirties, according to the results of a multitemporal remote sensing analysis (Rotondi and Zunica, 1995). The horizontal levels shown in the western back-dune plane are possibly due to the presence of silty-clay levels deposited during marshy phases. The strong localised reflections observed in the dune body are produced by buried shrubs and the strong reflection at the centre of the dune apparatus is probably caused by the presence of a dump. It is noteworthy that the area with no reflections, under the down-wind side of the dune was interpreted as a zone of high GPR signal attenuation for the rising salt-brackish water, favoured by the chaotic distributions of the sand grain for the grainfall deposition mechanism, and caused by heavy pumping of irrigating water. Though no groundwater table inside this dune was detected with GPR survey, as usual in sedimentary basins, the transition from fresh to salt water (brackish water) was indirectly pointed out by the high energy absorption and total reflection of the EM waves, occurring at this boundary, characterized by measured conductivity of 20-25 mS/cm and calculated concentrations beyond 25 g/l.

Evidence of its presence was found in the boreholes crossing the dune body, and in the literature (Anton, 1983), suggesting that a fresh water reserve lasts stored in dunes even for many months after episodes of rainfall, providing in this site, with a typical mean annual precipitation of 700-800 mm, a periodical recharge of the dune aquifer.

Because of the limits in penetration of GPR waves due to the presence of high salinity groundwater, the electrical survey, based on Vertical Electrical Soundings (VES) and conductivity measures in manual drillings (fig. 3), provided additional information on the subsurface structures and groundwater features, compatible with the GPR profiles. The SEV interpretation gives information on the water table depth and a best definition of the boundary between salt-brackish water and fresh water. In this way, it was possible to evaluate the local thickness of the fresh-water aquifer.

In fig. 4 the difference between the shore neighbouring of the sea (VES 1) and the front of the dune (VES 2) is slight and in both of them it is possible to recognize the salt-groundwater presence in very conductive layers with resistivities varying between 1 and 3 $\Omega \cdot$m. The VES 3 and VES 4, located respectively over the dune apparatus and in the back dune plain, give apparent resistivity curves proving the evidence of a shallow very resistive layer (1500/600 $\Omega \cdot$m), formed by dry and partially fresh-water saturated sands, and an underlying layer, with middle values of resistivity (20-30 $\Omega \cdot$m), corresponding to the fresh-brackish sandy aquifer, «floating» on the heavier conductive salt-water.

By the analysis of the groundwater and formation resistivities it was possible to calculate the typical formation factor of the investigated sediments, consisting in medium sands with silt-clay fractions lower than 2%. Using the simplified Archie formula (Archie, 1942) the formation factor (F) depends on the ratio of measured formation resistivity and pores saturating water resistivity ($F = \rho_a / \rho_w$, where ρ_a is the formation and ρ_w is the sole grounwater resistivity value): the mean local value obtained is 3.8. Therefore, extending the VES investigations to wider areas with geological features similar to the tested one, it's likely to obtain ρ_w and to define, through comparative charts, the total fluid salinity value.

The aforesaid study (Rotondi and Zunica, 1995), based on surveys carried out in 1931,

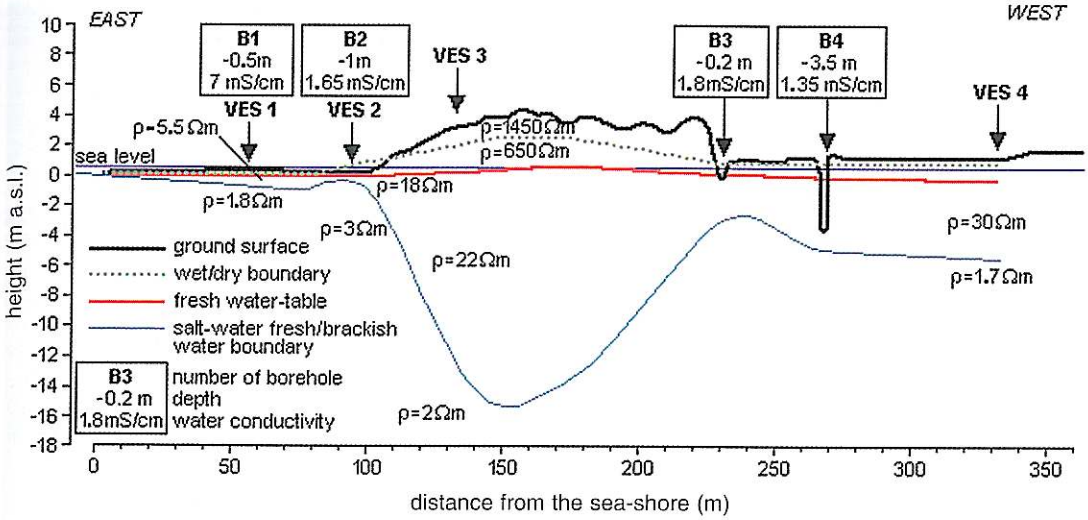

Fig. 3. Cross-section along the former GPR profile, summarizing the informations coming from VES, GPR and boreholes investigations.

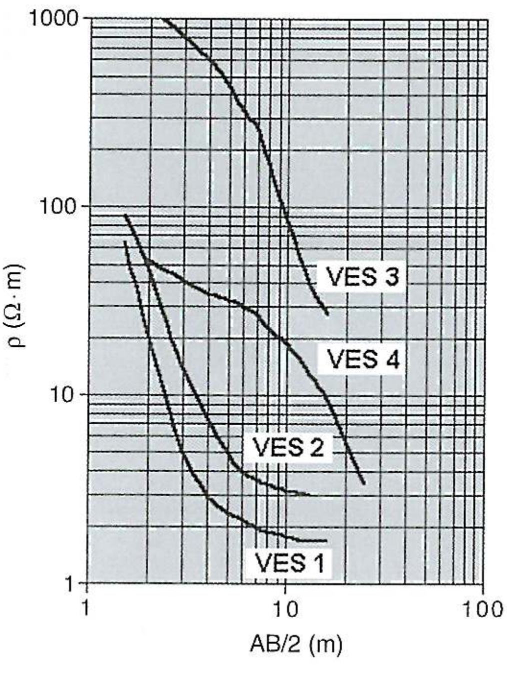

Fig. 4. Apparent resistivity plots, showing the electro-stratigraphic features close to the sea (VES 1), on the beach (VES 2), on the dune apparatus (VES 3) and on the back-dune plain (VES 4).

1968 and 1978, with references to 1892, and aerial photographs of 1994, recognized the shorelines at those four dates (see fig. 5) and the corresponding sand-dune complex.

As to the old coast lines, buried by recent sandy deposits, they show a good correlation with the radargram images produced by sloping reflecting surfaces dipping in the direction of the sea was found. Typical undulating reflections, referable to a sand-dune morphology in the same way buried by recent deposits and cutted on their top by anthropic clearings, are evident in reflective subparallel layers representing their encreasing phases. The topographic location of the most distant ones from the sea-shore is consistent with aerial evidence for 1931.

The continuous vertical sections provided by the radargrams makes it possible both to date some reflecting surfaces representing old sea-shores, and check their progressive motion, exceeding the fated limit of the aerophotographic scannings.

Moreover, a topographic survey along the georadar profiling line points out a limit of current (summer 1999) sea-shore, established with a tide level of +0.3/+0.4 m a.s.l.

Fig. 5. Aerial view of the investigated zone (from Rotondi and Zunica, 1995), with schematic marks of the coast line variations in the period 1931-1998 and of the GPR profile.

3. Conclusions

Traces of ancient buried coast-lines, progressing since the Thirties, according to the results of a multitemporal remote sensing analysis and some geophysical techniques have been focused. The advantage of GPR in coastal palaeomorphological studies is the possibility to obtain continuous vertical sections integrating discrete planar imaging series restricted to the very recent situation and to the particular times in which the images are recorded. Furthermore, the GPR is able to recognize the presence of salt-brackish water, through a total reflection of the GPR signal at the top of sediments saturated by high salt water content.

The importance of estimating fresh water reservoirs in this site is fundamental for planning irrigation water use in intensive horticultural activity of the area, restraining, in the dry season, the rise of salt water due to human heavy pumping.

The geophysical approach could be effective in countries with very dry climates, such as Egypt, where dune groundwater is used for vegetating dunes themselves, in order to stabilise and stop their migration (Munir, 1983).

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